Renewable and Sustainable Energy Reviews 22 (2013) 33–45

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Direct expansion solar assisted heat pumps: A review of applications and recent research

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ARTICLE INFO

Article history:
Received 14 June 2012
Received in revised form
7 January 2013
Accepted 14 January 2013
Available online 28 February 2013

Keywords:
Direct expansion
Heat pump
Cooling
COP
Exergy

ABSTRACT

Direct expansion solar assisted heat pump systems have widely been used in solar drying, water heating, space heating, space air conditioning and cold storage applications. With the high potentials of its efficient heat retrieving unit to effectively use low temperature solar energy, the investigation of the heating and cooling applications of the system has advanced within the past decade. Also, large numbers of refrigerants with high potentials for use in direct expansion solar assisted heat pump have been explored. Investigation results have shown ways of evaluation and various factors determining the performance of the system. These investigations are necessary in order to extend design and performance knowledge and to improve the technology in general. This paper summarizes various investigations and analysis of direct expansion solar assisted heat pump systems. The review rightly point out the obvious shortage of investigation in the cooling application area of the technology and suggest possible investigation area for improving its cooling applications.

Contents

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http://dx.doi.org/10.1016/j.rser.2013.01.029

1. Introduction

The concept of solar-assisted heat pump system has been of high importance among decision makers and experts in the energy industry. Issues regarding energy saving, energy efficiency and environmental improvement are among concern objectives as related to heating and cooling. Thus, the need to search for a less expensive, environmentally friendly system had led to use of solar energy, one of the most viable renewable energy sources.

A direct expansion solar-assisted heat pump (DX-SAHP) system is a technique of particular interest because it converts and transport heat energy from the sun (source) to water or absorbers (sinks). In comparison with other solar assisted heat pump systems, it has the ability to transfer heat for storage purposes. Direct use of high and low solar intensity efficiently for heating and cooling is also possible. This is achieved through the direct heating and expansion of the flowing refrigerant in the integrated solar collector–evaporator. Through the collector–evaporator modification, a reduction in the number of system units, reduced collector set up cost requirements and higher collector efficiencies have been achieved. However, some drawbacks such as the influences of heat source uncertainty, the need for proper component's configuration and heat loss are still reported in literatures. Various research studies have been carried out on fundamental of design and modeling and/or optimization of the systems performance, as well as field testing of pilot scale designed to overcome some of these drawbacks. This paper presents a review of the studies and investigations of direct expansion solar assisted heat pump systems. The review is organized into three major parts:

- Direct expansion solar assisted heat pump and applications.
- Designs components and configurations.
- Thermal performance characterization.

2. Direct expansion solar-assisted heat pumps

2.1. Review of the literature

Since the work of Sporn and Ambrose [1] which brings to light the concept of direct expansion solar-assisted system, various other works had been published in literature such as the work of Charter and Taylor [2], Franklin et al. [3], Chaturvedi and Mei [4] and others have contributed to the development of the technology. A schematic view of a direct expansion solar assisted heat pump is shown in Fig. 1(a)–(b). Fig. 1(a) depicts a DX-SAHP heating system comprising of three operation units namely, the heat retrieving unit, the work input unit and the heat delivery unit. It can be seen that both atmospheric heat and solar-radiated heat are harnessed by the collector–evaporator (heat retrieving unit). The compressor, the pump and the expansion valves are power consumption or work input units while, the heat gain is delivered at the conventional condenser side for heat exchange. Fig. 1(b) depict the operation units of a DX-SAHP cooling system which includes the heat retrieving units and the combined work–heat delivery units. The heat retrieving unit remains as in Fig. 1(a) while, the work input and heat delivery units are interlocked because of the application objective. This makes it slightly different from the conventional set up as the operational units do not follow the same order as in Fig. 1(a). The cooling application set up is similar to the vapor compression cooling set up with the inclusion of the collector–evaporator. The advantage is the ability to use the ambient and available solar heat to replace or reduce the work input for heat retrieving and generation to and from the system.

One of the early studies on DX-SAHP focused on using it as a means of multiple heat sources. This was investigated for cold climate as seen in the work of Krakow and Lin [5]. The solar collector–evaporator design was used as a pre-heater for heat pumps through the reuse of the heat provided to charge water for heat pumps. Also, a computer model developed for simulating the system was reported, Krakow and Lin [6]. Chaturvedi and Shen [7] found that a lower compressor speed and refrigerant mass flow rate result in higher refrigerant temperatures in the collector when investigating a DX-SAHP thermal performance. They obtained COP ranging from 4 to 9 and reported that higher water temperatures on the condenser outlet will result in decreased COP. The cooling performance of a refrigerant-filled collector heat pump was found to be inferior to conventional heat pumps by O'Dell et al. [8] when they studied the design method and performance of heat pumps with refrigerant filled solar collectors for heating and cooling applications. Kuang and Wang [9] obtained heating and cooling COP's of 2.7 and 2.9, respectively, for a multi-functional DX-SAHP system. The cold storage efficiency was about 30% and found to be less than the heating performance whereas the heating performance was concluded to be highly dependent on the solar radiation and a stable modulated compressor range.

Chaturvedi and Abazeri [10] reported that the system performance is highly influenced by the collector area, the compressor speed, the load temperature and refrigerant properties while the long-term influence of wind speed and storage volume on obtained COP's was low. The influence of various parameters on the collector performance was investigated extensively at different conditions by Ito and Miura [11], Ito [12] and Ito et al. [13]. They concluded that solar radiation influenced the evaporation temperatures and COP while the collector area increase gives small changes in COP. Hawlader et al. [14] reported a maximum COP and collector efficiency of 9% and 75%, respectively, for a given solar radiation range and a designed compressor speed. An economical payback period of two years can be achieved by the system. Chaturvedi et al. [16] obtained a COP between 2.5 and 4 from their experimental studies using a variable speed compressor.

Numerical and theoretical investigations of DX-SAHP reported in the literature include Kong et al. [17] analyses of a DX-SAHP water heater. Their results show that increasing wind speed gives increasing COPs and efficiencies but at lower solar radiation and ambient temperatures. A simulation study by Guoying et al. [19] obtained its highest COP of 4.69 using a hot water temperature at 55 °C. Also, Chow et al. [20] performed a numerical modelling of DX-SAHP for water heating and obtained a COP of 6.46. They discovered that various compressor speed designs result in higher COPs and high solar radiation leads to increased condenser heat gain. Hulin et al. [21] numerically studied a direct evaporator and a pond integrated evaporator. The highest COP ranged from 3 to 4 and 8 to 9 for the direct and integrated evaporator, respectively. The COP of the pond-evaporator was always higher for different heat loss coefficients test.

Nomenclature

COP	Coefficient of performance
DX-SAHP	Direct expansion solar assisted heat pump
H	Power supplied to the compressor (kW h)
H_t	Daily total solar radiation (W/m^2)
h	Specific enthalpy (kJ/kg)
ISAHP	Integrated solar assisted heat pump
m	Refrigerant mass flow rate (kg/s)
NA	Not available
Q_w	Daily total energy collection (W)
PV-SAHP	Photovoltaic solar assisted heat pump
SAHP	Solar assisted heat pump
s	Specific entropy (kJ/kg K)
TEV	Thermostatic expansion valve
T	Temperature (°C)
$T_{a,av}$	Mean ambient air temperature during operation (°C)
$T_{e,av}$	Mean evaporation temperature during operation (°C)
$t_{w,1}$	Temperature supplied to the water tank (°C)
t_e	Evaporating temperature (°C)

Greek symbols

ΔT	Temperature difference (°C)
$\eta_{\dot{E}x}$	Exergetic efficiency (%)
$\eta_{ex(sys)}$	Exergetic system efficiency (%)
$\dot{E}x_{gain}$	Exergy gain (W)
$\dot{E}x_{in}$	Input exergy (W)
$\dot{E}x_{lost}$	Exergy lost/destroyed (W)
$\dot{E}x_{out}$	Output exergy rate (W)

A two-stage DX-SAHP was reported by Chaturvedi et al. [22] to perform better than a single-stage DX-SAHP at high condensing temperature of 90 °C. The result shows a COP of 2.2–6.2 and it was observed that the COP increases as the refrigerant evaporative temperature increases. The collector efficiency decreases as the condensing temperature increases for the same power consumption and it was concluded that increasing the solar collector area is required to improve thermal performance.

A value of 10% was given as the COP average reduction amount by Anderson et al. [23] in their condenser integration modification and concluded that an increased area of the condenser in contact with the water tank improves the performance of the

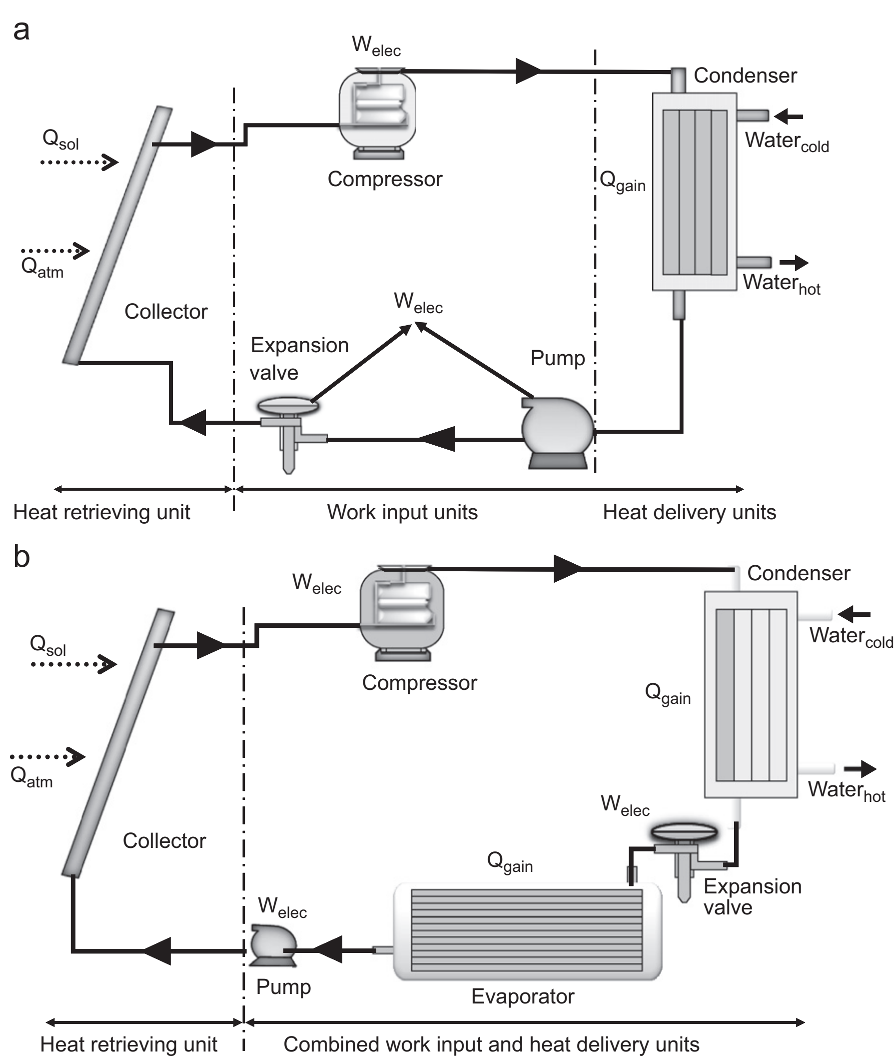

Fig. 1. Schematic view of a direct expansion solar assisted heat pump system, (a) heating and (b) cooling.

system. Chyng et al. [24] theoretically and experimentally investigated an integrated solar assisted heat pump (ISAHP) water heater and obtained a COP value above 2.0 for most of the time in a year at varying operating time of 4 to 8 h. An ISAHP for water heating coupled to gas burners obtained high COP values up to 8 and occurs at low compressor speed Scarpa et al. [25]. They concluded that the ISAHP offers a better performance of free energy use, including cold months, and the required energy (electricity) is very small. Gang et al. [26] obtained PV efficiency of 13.2%, PV-SAHP COP of 9.5 and a conventional SAHP COP of 6.3 for a DX-SAHP designated as a PV-SAHP in their experimental study. The average COP of SAHP was stable while the PV-SAHP COP rises and decline as condensing water temperature increases but the PV-SAHP was observed to perform better.

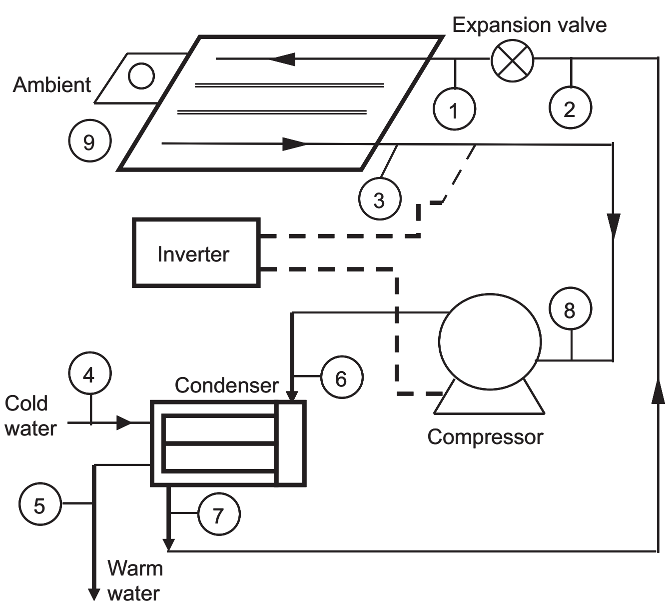

Fig. 2. Schematic view of a DXSAHP system by Chaturvedi et al. [16] (reproduced).

Hawlader et al. [18] applied DX-SAHP for solar desalination applications (as shown in Fig. 3) and obtained a varying system COP between 5.0 and 7.0. At increased feed water superheated degrees, distillate production increases and COP generally decreases with time during the experiment.

The exergetic efficiency studies by Li et al. [27] shows that the highest exergy loss occurred in the compressor and collector–evaporator, followed by the condenser and expansion valve, respectively. They obtained a COP of 5.21–6.61 and collector efficiency 88–105%. Results of exergetic studies by Torres-Reyes et al. [28] shows that low exergetic efficiency exist in solar-assisted heat pump operations while, the largest irreversibility occurs at the collector–evaporator, followed by the condenser, compressor and the valve. Torres-Reyes and Cervantes [29] report that exergy efficiency increases with increasing heating load and their new model result agrees closely with the performance of real systems. They obtained COP between 2.56 and 4.36 while the condenser and evaporator conductance was found to vary with the climate conditions during the experimental tests. Collector–evaporator was reported to have the highest exergy loss while heat losses coefficient of the collector–evaporator increases at increasing wind velocity by Cervantes and Torres-Reyes [30]. They found out that optimal evaporation temperature reduces as overall coefficient for heat losses of the collector–evaporator increases in their DX-SAHP exergy analysis.

Further experiments using exergy analysis by Ozer et al. [31] obtained calculated individual component's exergy efficiency ranging from 10.74% to 88.87%. The highest exergy destruction occurred in the compressor, followed by the condenser, the solar collector, the thermostatic expansion valves (TEV) and the circulating pumps. Mohanraj et al. [32] theoretically and experimentally used artificial neural network (ANN) to undertake exergetic studies. The system average exergy efficiency is 0.26% with an ANN correlation coefficient of 0.9472. Solar collector has the highest exergy destruction while, the exergy efficiency decreases at higher solar intensities. This was followed by the condenser, compressor and expansion valve. In another exergy assessment study, the same authors Mohanraj et al. [33] theoretically investigated R22 and RM30 refrigerant. Overall exergy performance of

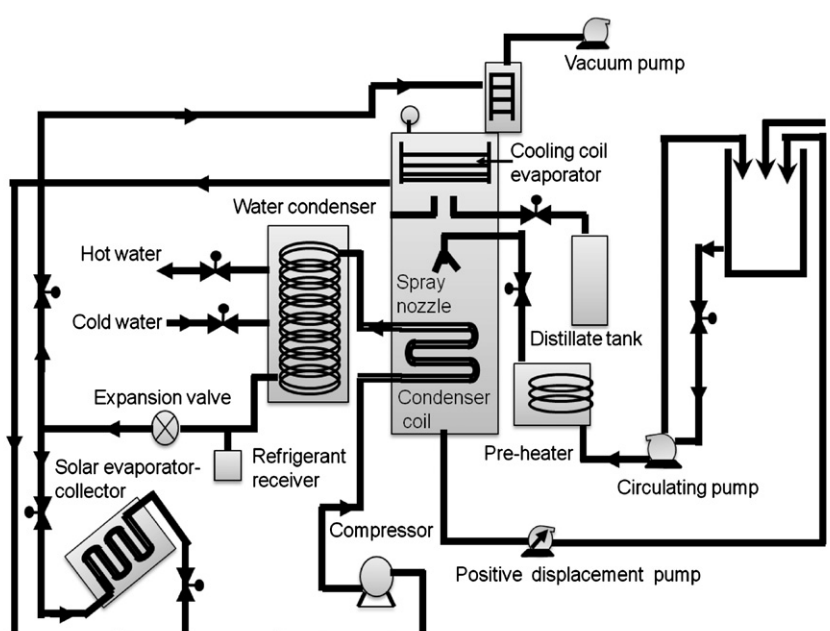

Fig. 3. Schematic view of a DX-SAHP desalination system by Hawlader et al. [18].

RM30 was slightly lower than R22 for different ambient conditions of a DX-SAHP. Greatest irreversibility was reported to occur in the compressor from a numerical energy-exergy analysis studies by Liu and Zhang [34]. A COP of 3 was obtained from their analysis while, increasing the number of solar collectors in parallel increased the system's COP and exergy efficiency. A decrease in pressure drop was observed and the rate of irreversibility decreases with increasing solar collectors in parallel.

In summary, the literature review shows that all issues pertaining to the performance of a DX-SAHP system have been investigated partly or in full. Further studies will be noted in relevant sections of this review.

2.2. Application of DX - SAHPs

Day and Karayiannis [39] presented a comprehensive classification of solar assisted heat pump in their review of its research and development. They categorised DX-SAHP systems together with multi-source solar-assisted heat pump systems. They pointed out that its ability to source for heat used to expand flowing refrigerants from available ambient temperature together with/or in the absence of direct solar radiation allows it to be referred to as a dual source solar assisted heat pump system. The two major classification of DX-SAHP application is namely heating and cooling. At both instances of application, an illustration of their operation in meeting demand for a particular period of time in a day is presented in Fig. 4 for both heating and cooling. The potential of the system is shown in the operation pattern over the time of solar energy availability. During the consumption of the available solar energy through direct usage, a measured amount of storage can still be achieved. The heating and cooling demand could be met directly when the available energy is highest and the stored energy could be used to assist or provide for small consumption at low solar energy availability.

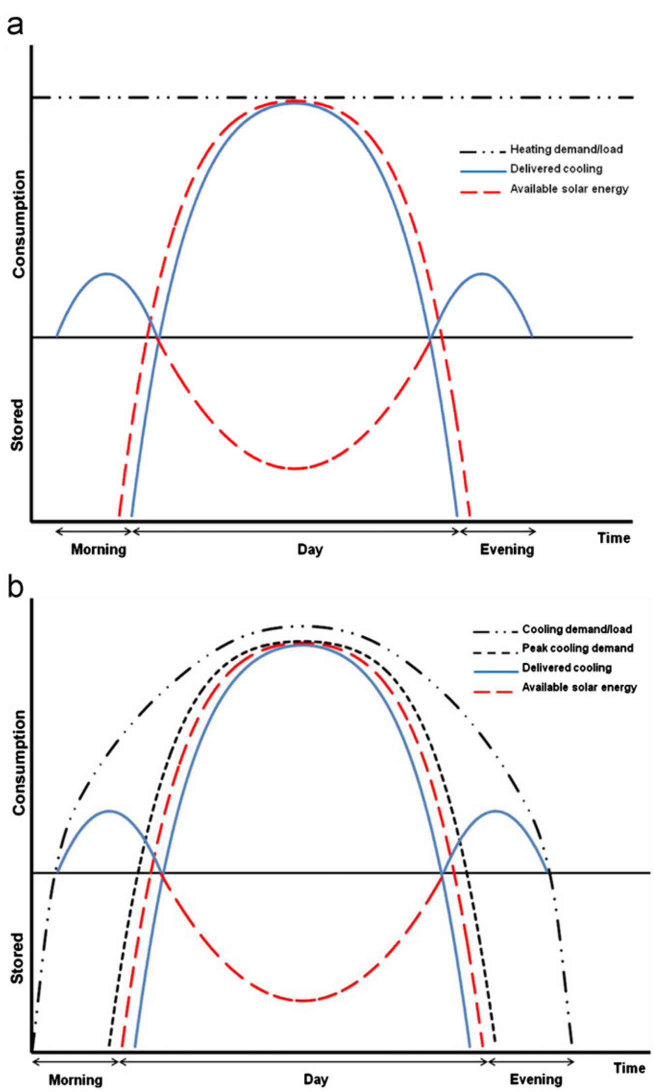

Fig. 4. Application operation pattern of DXSAHP system for (a) heating and (b) cooling.

2.2.1. Heating application

Most studies on DX-SAHP description have mainly focused on the benefit for all kinds of heating applications. Comparison of the application areas is depicted in Fig. 5 and shows that 75% of the literatures reviewed in this study have been attributed to DX-SAHP heating applications. It goes on to show it commercial viability for water, space and floor radiant heating. Thus, many heating demands are been met in domestic or household, hospitals, production industries and service establishment like hotels and restaurant. In this mode of application, it is obvious that DX-SAHP systems have recorded a high technical and commercial performance when compared with other forms of solar assisted heat pump systems.

2.2.2. Cooling application

The use of solar energy for cooling is an obvious advantage as the cooling demand increases when the incident solar radiation is at its peak. The sun offers the maximum possible solar radiation on days that require greatest need for cooling [40]. The DX-SAHP supplies the solar energy that replaces electricity at the thermal storage tank or generator to drive compressors for cold production. Studies available for DX-SAHP cooling review were found to be very few and relatively scarce. The set up of the system for cooling is different from other types of solar assisted heat pump and obtained cooling performances are reported to be low compared to conventional solar assisted heat pump systems. Kuang and Wang [9] experimental set up for a multi-functional direct-expansion solar-assisted heat pump system follows the order depicted in Fig. 1(a). For the cold storage function, the refrigerant flow direction is reversed while the compressor is switched on to heat up pre-heat refrigerant coming from the hot storage tank. The same collector–evaporator now takes advantage

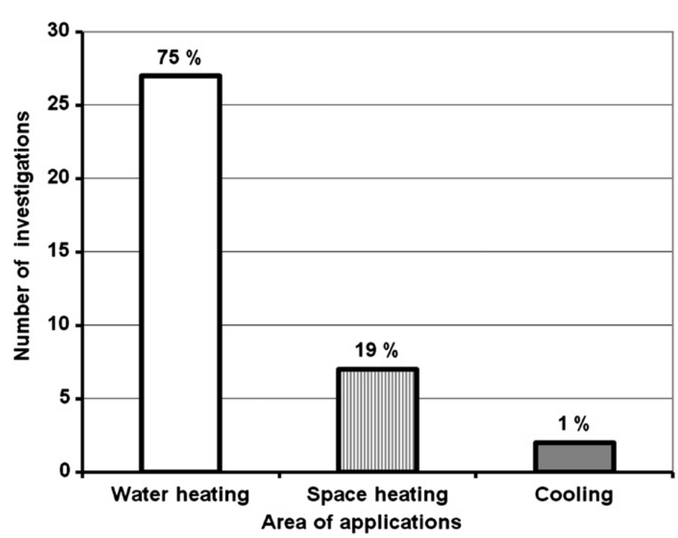

Fig. 5. Comparison distribution of DX-SAHP system application area from literatures review.

of the cold night wind and ambient temperature to cool it (serving as a condenser). This is stored in a cold storage tank for use during period of high ambient temperature (e.g. day time). The cold storage performance efficiency was 30% storing about 49.5 kW h of cold energy and having a COP of 2.9. As reported by O'Dell et al. [8] in their studies on heat pump designs, cooling performance of refrigerant-filled collector heat pump are inferior to conventional heat pumps. This lower compared performance is a limitation of high importance necessary to overcome for DX-SAHP cooling to have a favourable competitive ground with other types of solar-assisted heat pump systems for cooling.

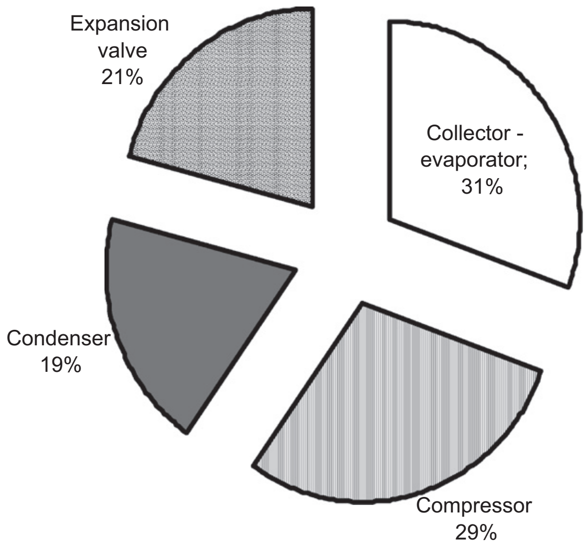

Fig. 6. Reviewed research work on DX-SAHP system components.

3. Design components and configurations

3.1. DX-SAHP components and investigated parameters

To ensure long-term thermal performance of DX-SAHP system, the component's sizing and configuration of the DX-SAHP components must match the demands for load and the daily radiation at the given location. Generally known DX-SAHP systems are made up of four main components and are configured based on the architectural design of the application facility or structure. These components are the collector–evaporator, compressor, thermal expansion valves and the storage-heat exchanger tank. Literature review on DX-SAHP systems revealed that the collector evaporator and the compressor are common components that are highly influenced by the amount of heat obtained from the heat source. Moreover, the power consumption occurs at the compressor and pumps which the collector evaporator performance in turn depends on. Reviewed work evaluated in this review shows the influence of the available solar heat on the performance of both the collector evaporator and the compressor to be highly significant. To a very large extent, these two components have adequately reported in most DX-SAHP research work. As shown from Fig. 6, the collector–evaporator accounts for 31%, compressor for 29% while, 21% and 19% represent the condenser and expansion valve accounts, respectively. Since each component's performance influence the total system performance, designing them has been evaluated based on certain performance parameters. Table 1 summarizes different component types and their parameters for different studies.

3.1.1. Collector–evaporator

The two major types of collector–evaporator mostly employed in DX-SAHP system applications that research woks have focused

Table 1
Different component types and parameters investigated with them for different studies.

Components	Types	Investigated parameters	References
Collector evaporator	Unglazed	Collector efficiency, collector design, collector area, wind speed, load temperature and refrigerant properties, collector area, water temperature and ambient conditions	[7–10,14,16,29]
		Solar collector surface, refrigerant quality, heat transfer coefficient, heat capacity, evaporation rate, ambient conditions and operating mode	[15,19,21,28]
	Glazed	Collector area, different refrigerants evaporation, ambient conditions and pressure drop	[32,36,37,40,42]
		Collector area evaporative capacity, collector efficiency, performance ratio	[18,22]
	Photovoltaic modules	Temperature, pressure loss, solar radiation, wind velocity and heat output rate	[35,41]
	Vacuum and evacuated	Wind velocity, ambient conditions, PV temperature, mass flow rate, PV power output, condensing water	[26]
Compressor	Rotary hermetic type	Pressure loss, compressor power, wind velocity, material, mass flow rate	[11,13,41]
	Reciprocating	Operating mode and compressor heating capacity	[17,19,27,43]
		Compressor speed, power input,	[14,20,35,44]
		Fuel depletion ratio and component irreversibility rate/factor	[31]
		Pressure drop, power consumption, performance ratio, compressor temperature and heating capacity	[32,42]
		Performance with R22 and RM30	[33]
		Influence of expansion valve adjustment and compressor speed	[24]
	Variable frequency reciprocating	Compressor speed and variation, mass flow rate, power input and pressures drop	[7,9,14,16]
Condenser	Water tank delivery	Ambient conditions, tank stratification, heat transfer rate and coefficient, heat pump capacity, energy storage and efficiency, storage volume.	[8,24,41,43]
		Condensing water output and temperature, operating modes and operating time performance	[14,19,26]
	Air delivery	Ambient conditions, heating capacity, energy storage and efficiency, Pressure, condensing water outputs	[8,9,32,33,42]
	Water spraying	Water inlet temperature and flashing effect	[18]
Expansion valve	Thermostatic	Exergetic performance	[27,31,32]
		Mass flow rate and online effect	[14,24]
		NA	[9,16,17,33,41,43]
	Capillary tube	NA	[20]
	Electronic TEV	NA	[7,26]

on are the unglazed and glazed flat plate solar collectors. Both of them have been extensively used for DX-SAHP systems research studies and are summarized in Table 1. It presents both the glazed and unglazed collector types as used by various references. Among the two types, it is clear that the unglazed flat plate collector is the most widely used. The use of unglazed type flat plate has been encouraged by its ability to obtain good collector efficiency. In the absence of collector covers, heat loss transfer activity is reduced because all available heat absorbed by the plate is transferred to the low temperature flowing fluid. This main advantage of recovered saving by the collector–evaporator modifications have been cited by many research works for DX-SAHP systems application. Early investigation by Krakow and Lin [5,6] used finned coil collector–evaporator design for absorbing ambient temperature as heat source instead of solar collectors. An output temperature of 2.8 °C above actual ambient temperature was reported as the solar energy effect.

Other types of collectors include the vacuum tube, photovoltaic thermal modules and evacuated tubes have all been experimented with when investigating DX-SAHP systems. They have shown to give high temperature difference and added up to the overall efficiency performance at the heat source side of DX-SAHP systems. Gang et al. [26] combined Photovoltaic modules with heat pumps to investigate the performance in a typical climate zones and obtained an overall PV-SAHP COP of 9.5. A U-pipe evacuated tube was used by Raisul Islam et al. [35] for their transcritical cycle performance study on solar assisted heat pump water heater using CO_2. This provides collector efficiency calculated to be in the range of 50–55%.

Since solar radiation is the main source by which solar energy is transferred, reducing heat losses through designs at the point of conversion has largely been considered in determining system performance. By so doing, certain parameters such as collector's dimensions and material, dimensions of pipe carrying the fluids and properties, fluid mass flow rate, wind velocity, ambient temperature and amount of solar radiation are investigated at the solar collector-evaporator unit. Practically, the ambient temperature and amount of solar radiation are the most important parameters but their high instability is a concern. Thus, much investigation focusing on the collector's dimensions and material type factor makes it the most important design parameters. Collector area increase was reported to give small changes in COP of the system when investigated by Ito et al. [13]. Parameters measured at other component such as the compressor unit and the condenser or storage unit are important factors for other parameters to improve heat loss factor reduction.

3.1.2. Compressor

In compressor units of most DX-SAHP system, compressor speed and efficiency are two determining parameters in its function of raising refrigerant pressure and increasing heating temperatures. However, they can be considered used below their capacity or been less efficient if the desired output temperature for the application is not delivered or when its delivery does not correspond to the available solar radiation giving the fact that it could be high or low. This later factor of mismatch between compressor speed and instability of the available solar radiation is recorded to highly influence the performance of the compressor by most researchers. Literature reviews have shown a better compressor performance by using a variable speed compressor. Chaturvedi et al. [16] obtained a COP range between 2.5 and 4 from their experimental studies using a variable speed compressor. Another report shows that various compressor speed design resulted in higher COP and high solar radiation resulted in increased condenser heat gain in a DX-SAHP water heater [20].

It is suggested that keeping the compressor speed at low speed will not only improve COP, it will also prolong the service life span of the compressor. Decreased compressor speed from 1500 to 900 improves COP by an average of 57% when using CO_2 in a trans-critical cycle Raisul Islam et al. [35]. Also, Chaturvedi et al. [16] results indicate that reduced compressor speed down to 30 Hz and increased ambient temperature improves the COP up to 3.75. They concluded that, a higher compressor speed up to 50 Hz and decrease in ambient temperature will reduce the COP to around 3.0. Maximum collector efficiency of 88.4% and higher performance ratio ranging from 0.77 to 1.15 according to Hawlader et al. [18] have been reported for increasing compressor speed and solar intensity. This outcome in compressor speed and solar intensity according to Raisul Islam et al. [35] was reported to produce increased rate of heat output. However, it has shown that it might not match with the ambient temperature which will in turn lead to low COP [7,18,35].

Another advantage of achieving higher COP through compressors is the opportunity of reducing the compressor energy consumption. Studies have shown that power consumption of compressor is represented by the empirical functions of the evaporation temperature and water temperature at the condenser [5]. Comparing between short- and long-term performance studies, Morrison [15], obtained higher COP for short time (6 h) compressor operation than for longer time.

Other measured parameters reported to influence the compressor performance include expansion valve effects, the storage volume or load and the efficiency of the compressor [7,9,16]. Hermetic rotary type and reciprocating type compressor with rated power ranging from 10 W to 800 W has been employed in most DX-SAHP systems.

3.1.3. Condenser

Apart from the cooling application configuration, most condensers basically function both as heat exchanger and storage tank sometimes for DX-SAHP application. Copper tube piping has been used in most water heating application for the refrigerant flow and heat exchange with the cold water in the water tank. For space heating, it follows the same operating principles. Hawlader et al. [14] reported on an investigation using fibre glass made water condenser tank. Furthermore, a condenser with a spraying tube water supplier was used for solar assisted heat pump desalination system and reported by Hawlader et al. [18]. Technical condenser performance depends on how well it is design to reduce heat loss through radiation. Also, the coil size is another very important parameter especially for the cooling application. The optimal velocity of the refrigerant necessary for the optimal pressure should determine the coil size selection. However, literature result has been much concerned with design parameters that relate it with other system components. Chow et al. [20] numerical modelling of a DX-SAHP for water heating indicates that increased condenser heat gain can be influenced by various compressor speed design. By so doing, higher COP and high solar radiation were obtained. In this regard, properties of the condensing refrigerant or fluid such as the heat transfer coefficient of the refrigerant, water and the ambient air temperature are important factors considered for condenser design and performance. Stratification effect in the tank is also of importance if storing of the heated water for future usage is part of the objective. Anderson et al. [23] experimental studies show that heat transfer into the tank at full heat-up cycle uniformly distributes heat over the tanks surface while, heat is transferred in the lower portion of the tank for both the half and short cycle test. They concluded that increased area of the condenser in contact with the water tank improves the performance of the

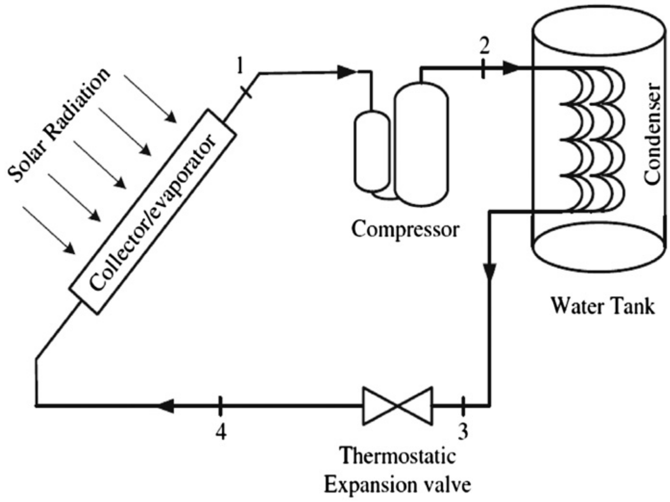

Fig. 7. Schematic view of a DXSAHP system by Kong et al. [17].

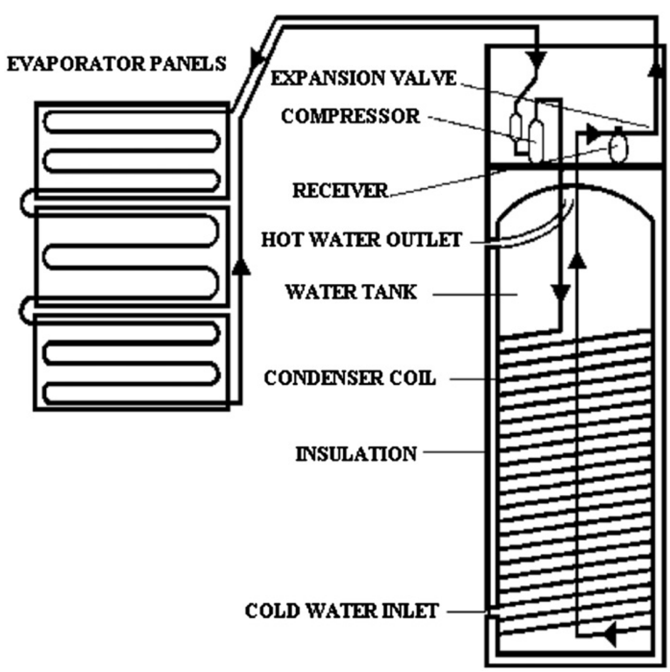

Fig. 8. Schematic view of a solar-boosted DXSAHP system by Anderson and Morrison [43].

system. Thus, to enhance heat transfer by increasing the heat transfer area for DX-SAHP system, addition of fin to the piping can be employed. This is a well-established method in heat exchanger pipes but has not yet been fully reported in the literature for DX-SAHP condensers.

3.1.4. *Expansion valve and pump*

In order to maintain a proper matching between the heat pumping capacity of the compressor and the evaporative capacity of the collector–evaporator under widely varying ambient conditions, the electronic expansion valve and variable frequency compressor are suggested to be utilized for the DX-SAHPWH [27]. The expansion valve enables the pressure of the refrigerant from the condenser to drop and adjusts the flow rate of the refrigeration. The expansion valves are of various types because of their activity that has been shown to significantly influence the oscillating characteristics of the compressor power and refrigerant mass flow rate [7]. Apart from the popularly used thermostatic types, electronic and capillary tube types have also been employed in investigating DX-SAHP systems [7,20,26].

3.2. *Configurations of DX-SAHP systems*

Presently, there is no specified number of configuration modes agreed upon for DX-SAHP systems configurations because they all follow similar pattern of operations based on the application demand. For convenience and based on reported research works, this review divided the configurations into two main categories namely ‘basic models’ and ‘advance models’.

3.2.1. *Basic configuration models*

The basic model which is the most investigated model involves the heating and expanding of the liquid refrigerant to vapour in the collector–evaporator. It is further heated up and given off as a high pressured hot vapour by the compressor. The hot vapour refrigerant at high pressure is then transferred into the storage-heat exchanger medium for water heating purposes as well as space and floor heating purpose. This has been reported by a lot of researchers and is characterized by low cost and simple set up because of the less number of components needed for the set up. It is of importance to point out that heating purpose has been the major area of application for this mode of configuration. Figs. 1, 2, 7 and 8 are examples of typical schematic views for many basic configurations.

3.2.2. *Advance configuration models*

The advance model configurations [9,22,24–26] follow the same operation pattern as the basic model but involve extra components or combining the system as a whole with other system. An experiment was performed by Kun and Wang [9] to investigate the performance of a multi-functional direct-expansion solar assisted heat pump system. It was set to operate at different operation mode for various weather conditions. The refrigerant-filled solar collector function was varied by reversing the refrigerant flow direction at the four-way valve to serve the different purposes. Gang et al. [26], integration involves combining the photovoltaic evaporator to a conventional air source evaporator such that, at low solar radiation and consequently low photovoltaic performance, the ambient air was maximized. Figs. 9 and 10 depict a two-stage direct expansion solar-assisted heat pump for high temperature applications using low and high pressure stage compressors [22] and a performance analysis of a proposed integrated solar-assisted heat pump water heater by [24].

Parametric studies of various configurations as it affects the COP and their dependence on solar radiation and ambient temperatures on the long term performance have been the main objectives of reported studies. It was obvious that the advance configuration models perform better than the basic models in terms of the reported COP which makes them recommendable as having high performance potentials. In the cases of low COP, relative stable compressor power consumptions have been achieved, Kuang and Wang [9], while, other parameter that required the adjustment of expansion inlet and outlet flow were investigated, Chyng et al. [24]. Common objective of investigating the expansion valve adaptation to varying operation conditions shows to maintain a stable COP benchmark. However, it was considered to be low to other advance models COP as obtained from conventional DX-SAHP models. Also, the issue of higher investment cost has not been convincingly shown to be inviting by many of the studies.

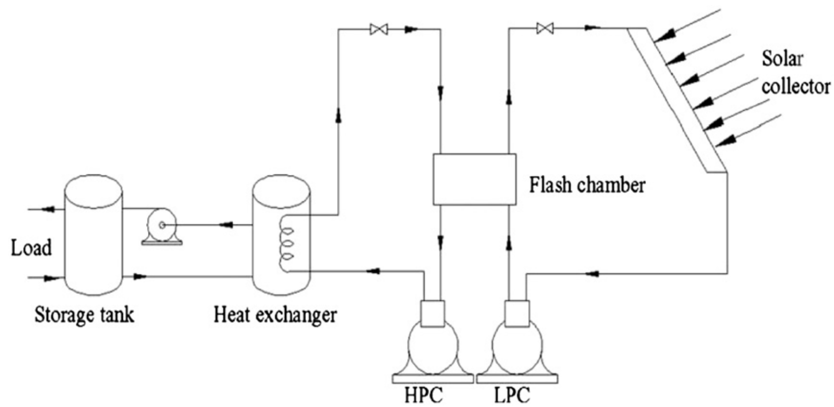

Fig. 9. Schematic view of the two-stage DX-SAHP system by Chaturvedi et al. [22].

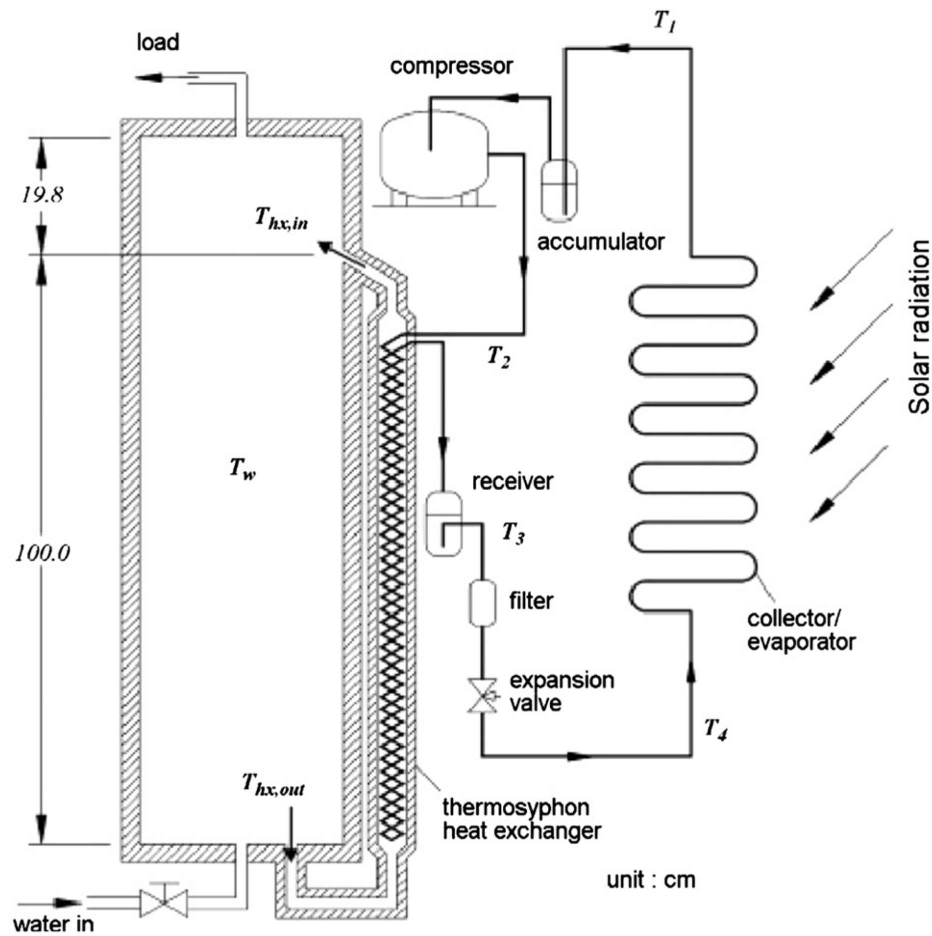

Fig. 10. Schematic view of the integral type DX-SAHP system by Chyng et al. [24].

3.3. *Refrigerant types used in DX-SAHP systems*

A good working refrigerant for DX-SAHP systems must posses a high thermal conductivity, critical temperature and evaporation enthalpy to achieve good heat transfer rate and high COP. It must also have certain qualities to reduce pump and compressor power consumption which includes very low freezing temperature, specific volume capacity and viscosity. Prevention of ozone layer depletion and environmental pollution are two issues that are initially of top priority in their selection criteria. Two main types of refrigerant in existence for DX-SAHP systems usage are plain refrigerants and mixed refrigerants. With the need arising for new, effective and environmentally safe refrigerant, mixed refrigerant has been reportedly been investigated for DX-SAHP systems. Mohanraj et al. [36] compared the performance of R22 refrigerant and a mixture of RM30 for DX-SAHP. RM30 was reported to have 3.5% lower heating capacity than R22 due to lower latent heat at higher operating temperatures.

Another study by Gorozabel et al. [37] to replace R12 with R134 shows system performance degradation was about 2–4% for collector temperature range of 0–20 °C. They further reported that the R12 COP performance was the highest followed by R22, R134A (15–20%), R410A and R407C or R404A. Aziz et al. [38] investigated the thermodynamic analysis of two-component, two-phase flow in solar collectors using R123 and R134A mixture for DX-SAHP application. Mass-flow rate and gained solar heat flux significantly affect the collector tube length and refrigerant heat-transfer coefficient. They also noted that the vapour quality of the refrigerant mixture increases gradually near the end of the tube. Performance are still low compared to the traditional primary refrigerant, but encouraging result showing high potential values for some mixture over others has also been reported by Mohanraj et al. [33].

4. Thermal performance characterisation in DX-SAHP

4.1. Performance analysis and evaluation

A detailed understanding of the availability of interdependent parameters and their interaction are required to accurately predict system thermal performance when designing a direct expansion solar assisted heat pump system. From both experimental and numerical investigations carried out to investigate the thermal characteristics of direct expansion solar assisted heat pump systems, various findings have been presented relating various thermal performance classifications and the influencing parameters based on the analysis type carried out. The types of thermal performance analyses have been classified in this study as used by various researchers for different performance evaluation. They are classified as coefficient of performance (COP) analysis, energy and exergy efficiency analysis and refrigeration efficiency analysis. Table 2 gives the list of the common thermal performance analysis carried out in the study of direct expansion solar assisted heat pump systems, findings and mode of presentations.

4.1.1. Coefficient of performance

Among the thermal performance analysis, coefficient of performance is the basic and predominantly performance evaluation approach analysed. It is defined as the ratio of the heating or cooling effect Q_{sys}, to the total work input W_{sys} required to achieve the heating effect COP_{sys}. This is true for every heat pump either as a stand alone or combined with refrigerating cycles and is mathematically expressed as

$$COP_{sys} = Q_{sys}/W_{elet} \tag{1}$$

In reference to Fig. 1, Eq. (1) can further be expressed for a DXSAHP system as

$$COP_{sys} = \frac{m_f Cp_f \Delta T_{h,c}}{(W_{comp} + W_{pump} + W_{valve})_{h,c}} \tag{2}$$

Here, the system heating or cooling effect is a function of the fluids mass flow rate, m, specific heat capacity, cp, and the temperature difference, ΔT. The subscript h, and c, represents heating or cooling state, respectively. The total work input is likewise a function of the summation of the work input to different system component. Other forms of expressing COP exist for most SAHP systems and can also be use to express COP in DX-SAHP. The compressor, pump and sometime the expansion valves are mostly driven by electrical energy. The performance characteristic of driving these component in SAHP and DX-SAHP system is termed primary energy ratio (PER) or energy efficiency ratio (EER). Due to the influence of exergy losses occurring at certain system components on the COP of the system, knowledge of the PER/EER is of

Table 2
Some DX-SAHP studies with thermal performance analyses type and mode of presentations.

Refs.	Study mode	Analysis	Result	Evaluation presentation
[9]	Experimental	COP	2.7 and 2.9	Function of power, solar radiation and temperature with time
[16]	Theoretical and experimental	COP	2.5–4.0	Function of ambient conditions, power and motor speed of the compressor
[22]	Theoretical	COP	2.2–6.2	Function of the condenser temperature and the collector area
[11,13]	Theoretical and experimental	COP	5.3	Empirical functions of the evaporation temperature and water temperature
[43]	Experimental	COP	6 and 4.5	Function of ambient conditions, Heat transfer and power to time for the heating cycle.
[44]	Analytical and experimental	COP	6.4	Function of ambient conditions, collector area, storage volume and compressor speed
[7]	Analytical and experimental	COP	4–9	Function of evaporating temperature, heat gain and compressor power
[14]	Theoretical and experimental	COP	4–9	Function of ambient conditions, compressor speed with time, storage volume, collector efficiency
[24]	Theoretical and experimental	COP	1.7–2.5	Function of output water temperature for varying solar insolation
[21]	Numerical	COP	3–4 & 8–9	Function of time
[26]	Experimental	COP	9.5 and 6.3	Function of condenser temperature, PV efficiency, time, power generated and consumed
[18]	experimental	COP	5–9	Effect of water supply rate and temperature, quantity of distillate collected, performance ratio with compressor speed and time
[34]	Numerical	Energy and exergy	$\eta_{ex}=34.27\%$	Exergy at the heating load to the collector - evaporator, with compressor and pump power consumption
[31]	Review and experimental	Exergy	NA	Fuel consumption and delivered heat
[32]	Theoretical and experimental	Exergy	$\eta_{ex}=0.24–0.28\%$	Both efficiency and losses as a function of solar radiation and ambient condition
[28]	Theoretical and experimental	Exergy	NA	Function of ambient conditions, temperature difference and time
[29]	Theoretical and experimental	Exergy	$\eta_{ex}=0.067–0.14\%$	Function of condenser heating load
[30]	Experimental	Exergy	$\eta_{ex}=0.067–0.14\%$	Function of solar radiation and ambient condition
[27]	Experimental	Exergy	$\eta_{ex}=10–30\%$	Function of time for useful component heat gained

importance [31]. This can directly be linked to the time and season of the DX-SAHP applications which provides another form of COP evaluation known as seasonal coefficient of performance (SCP). DX-SAHP COP can be evaluated as a season COP especially if the design is meant for both cooling and heating application. This is achieved by just computing for the regular COP during a particular season or period.

The COP which can also be presented as the heat pump effectiveness for DX-SAHP totally depends on the available solar radiation and ambient temperature for the desired performance outcome. This is because it determines how high the temperature generated at the evaporator can be evaluated. The highest evaporator temperature is in turn used to determine the effectiveness of the system by relating it to the temperature coming in from the completed system cycles. Kong et al. [17] reported that COP and efficiency increase as ambient temperature increases while, COP increases and efficiency decreases at increasing solar radiation temperature. Solar radiation was concluded to significantly influence the evaporation temperatures and COP for the performance of a heat pump using direct expansion solar collectors [13]. Guoying et al. [19] reported that the system highest COP was obtained at higher solar radiation and it increases at increasing ambient temperature. The highest solar input ratio was obtained at higher solar radiation but decrease at increasing ambient temperature.

4.1.2. Energy–exergy efficiency

Energy and exergy efficiency analysis have gained significant importance because of its ability to point out which part of the system component is performing less. This information allows necessary improvement to be carried out on it. The energy efficiency of a system or component can be expressed as the ratio of the summation of the real delivered heat by the flowing fluid, Q_d, and the real delivered heat as stored fluid, $Q_{d\text{-}st}$, for a range of time over the summation of the supplied heat to the flowing fluid, Q_{sp}, and the supplied stored heat from the energy input, $Q_{sp\text{-}i}$.

Q_d and $Q_{d\text{-}st}$, are both a function of the m, cp and ΔT based on the kinetic state of the fluid (i.e. flowing fluid for Q_d and stored fluid for $Q_{d\text{-}st}$). Q_{sp}, is a function of the geometry dimensions for heat transfer and the measured solar insolation and ambient temperature over a range of time. $Q_{sp\text{-}i}$, is a function of the energy input to aid the supplied heat to and from the flowing fluid and storing it. This is expressed mathematically as

$$\eta_{(sys,\ \ component)} = Q_{gain}/Q_{in} = \frac{Q_d + Q_{d\text{-}st}}{Q_{sp} + Q_{sp\text{-}i}} \tag{3}$$

In expressing the exergetic analysis for the efficiency and losses, the same general form of energy balance equation, (Eq. (4)), is employed. The difference is only the identification of losses accounted for when exergy analysis is made for presenting either the system or its individual components or units. This is indicated by the second term on the right hand side of Eq. (5).

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{4}$$

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{lost} \tag{5}$$

Thus the exergy efficiency will be the ratio of the total exergy gain to the total exergy input. Both are expressed in Eqs. ((6) and (7)), respectively; where m is the refrigerant mass flow rate, h is the specific enthalpy, s is the specific entropy, T is the temperature and 0 stands for the initial state of the refrigerant.

$$\dot{E}x_{gain} = m\ \ [(h - h_0) - T_0\ \ (s - s_0)] \tag{6}$$

$$\eta_{\dot{E}x} = \ \ \dot{E}x_{gain}/\dot{E}x_{in} \tag{7}$$

The exergy performance analysis describes the useful heat gain or delivered by the system and is commonly referred to as the heating capacity in regular heat pump system. This analysis benefit is extended to the DX-SAHP systems as it posses the capability of describing the effects of both the solar radiation and ambient temperature effects on the system components. According to [31], DX-SAHP exergetic study has been quite few. However, they have been able to provide valuable outcomes in improving DX-SAHP system performance as it depends on factors like wind speed, compressor speed, operation time, collector–evaporator sizes and arrangements [29,30,34]. At an average temperature difference of 12 °C, Cervantes and Torres-Reyes [30] used the effects of solar and ambient air temperature in the collector–evaporator on the exergy efficiency performance to present the thermodynamic cycle performance of a solar heat pump. Other research showed that the solar radiations and ambient temperatures affect the exergy performance [28,32]. The exergy efficiencies reported has not followed the same evaluation pattern thereby, making it difficult to adopt certain order of magnitude, figures or numbers range in general for the exergy efficiency. Some where evaluated and reported for the system as a whole [27,32–34]. Others were separately evaluated and the individual component's exergy efficiency was compared [27,31,41]. Lastly, some studies such as [27,32–34], reported on evaluations carried out for both the whole system and individual components. The exergetic efficiency values for some studies are presented in Table 2 and were observed to be in the ranges of 0.067% [30] to 34.27% [34]. These values represent the results of evaluations for complete system exergy efficiencies. As highlighted in Table 2, several authors have obtained the systems exergy efficiency values as a function of different parameters. The obtained highest exergy efficiency reported was 34.27% from a numerical study by Liu and Zhang [34]. As noticed from Table 2, a very low exergetic value of 0.067% was obtained by Cervantes and Torres-Reyes [30]. However, these values increase to give a maximum exergy efficiency of 0.14%. In their experiment, the other significant ambient condition parameter investigated along with the solar radiation is the wind velocity. As it increases, the heat loss at the collector–evaporator increases. This in turn results in decreasing exergy difference at the condenser which when computed with the constant power feed to the compressor produce a lower exergy efficiency value. The most profound exergetic efficiency result reported for evaluations that were focused only on individual components, was by Ozer et al. [31] for efficiency ranges from 10.74% to 88.87%.

An important benefit of the exergy analysis considering different application areas, sizes and materials of component used is the identification of occurrence point of exergetic losses. Different research work has followed the same pattern in identifying exergetic losses when designing the DX-SAHP systems. Liu and Zhang [34] energy–exergy analysis studies indicate that the greatest irreversibility occurs in the compressor. Li et al. [27] reported that the highest exergy loss occurs in the collector–evaporator for smaller DX-SAHPWH and at the compressor for larger DX-SAHPWH in their study. In all, major exergy loss has been reported to occur mostly at the compressor [28,30,32] or at the collector evaporator [31,34].

4.2. Classification of performance characteristics

Classification of influencing/depending parameters are generally investigated in modelling the direct expansion solar-assisted heat pump systems to enable the transfer and general application of gained knowledge from any study. This is necessary as similar parameters influence the system everywhere it is applied. For

numerical, theoretical and experimental studies, investigations of various parameters can be classified into;

(a) Conditional-based classification.
(b) Non-conditional based classification.

The names of the two classes are self-explanatory, it is observed that no single one exist alone during modelling or operations of a DX-SAHP system. The conditional classification focuses on the parameters used in the models that are notable for un-predictable performance or availability. This turn out to be one of the main and essential constituents of the system itself and efforts have been made to achieve high conversion and maximization of it whenever available. The non-conditional class happens to be the variables that could be used and are of standard measured values. They could be fixed when modelling and during operation. Typical conditional based classification parameters list include; solar radiation, ambient loadings effect, different modes of operations or conditions, heat gained at the condenser, heat transfer and refrigerant properties. For the non-conditional based classification, collector–evaporator area and physical sensitivity analyses effect, water volume, compressor's energy consumption and compressor speed (including mass flow rate and pressure) make up the list.

In most cases, both classification patterns are adopted when modelling partly because calculations have been able to relate them together and no real calculation barriers have been reported. Different correlations have been presented [24,41,45]. However, it is noticed that direct usage of developed result for the system design in other studies have not extensively been investigated. This is an area where the classification of the influencing parameters is presumed to be of benefit. Comparing the following performance correlation equation presented by Ito et al. [41] and Chyng et al. [23], it is observed that the depending parameters used are different. This can be attributed to the condition under which they are obtained. Eqs. (7)–(9)) by Chyng et al. [24] did not consider heat supplied in other forms in their correlation when compared to Eq. (10) by Ito et al. [41] that resented it by relating it to the condenser temperature.

$$COP = 0.0019\ (t_{w,1} - t_e) - 0.0231\ (t_{w,1} - t_e) + 8.40 \tag{8}$$

where

$$H = 3.24\ t_{w,1} + 1107 \tag{9}$$

$$Q_w/Ht = 2.36\ \left[\frac{(T_{a,av} - T_{e,ev})}{Ht}\right] + 0.53 \tag{10}$$

In the expressions above, $t_{w,1}$ is the temperature supplied to the water tank, t_e is the evaporating temperature, H is the power supplied to the compressor, Q_w is daily total energy collection, H_t daily total solar radiation, $T_{a,av}$ is mean ambient air temperature during operation, $T_{e,av}$ is mean evaporation temperature during operation.

4.3. Future work

General area of further investigation still lies with improving DX-SAHP component matching for higher maximization and increase of the system efficiency over long period of time. In addition the two following highlighted points are areas where further research can be focused.

4.3.1. Defining scope of validations

Investigation into the development of more models and correlating it numerically for the system design and performance is very important especially towards easing the modelling of designs. This approach is presumed to be achievable considering the literature review and performance classification discussed in this review. This will provide an opportunity for expanding the application areas of the technology especially when combined with other system.

4.3.2. Innovative cooling

The need for investigating the cooling application is of paramount importance to attract greater interest in the system and enhance its market penetration. Moreover, shortage in information on different and possible enhancing techniques for direct usage of the heat gain at the condensing unit for cooling application is observed during this review. In addition, determining the optimal velocity for the refrigerant is very important for the coil sizing. These are believed to be areas of possible improvement for the space cooling application.

5. Summary

Direct expansion solar-assisted heat pump (DX-SAHP) systems have been used for instance consumption and storage of solar energy during heating and cooling applications. The DX-SAHP heating application commercial viability was shown to be high and accounts for 75% of the research papers reviewed in this study. The collector–evaporator accounts for 31%, compressor for 29%, while, 21% and 19% represent the condenser and expansion valves, respectively from research studies. Also, large numbers of refrigerants with good usage potentials in direct expansion solar-assisted heat pump have been shown to exist.

Reviewed work evaluated shows that the influence of the available solar heat on the performance of both the collector–evaporator and the compressor to be highly significant. Furthermore, the advance configuration models group of a DX-SAHP system perform better than the basic models in terms of the reported COP which makes them recommendable as having high performance potential for further investigation.

Based on difference performance evaluation approach used by various researchers, thermal performance analyses have been divided into the coefficient of performance (COP) and the energy/exergy efficiency groups in this study. Reviewed highest system exergy efficiency value of 34.27% was reported from a numerical study while, individual component's efficiencies were reported to be within the range of 10.74–88.87%.

Various parameters are classified as 'Conditional based' and 'Non-conditional based'. Ability to relate them together with no real calculation barriers partly enables the adoption of both classification patterns when modelling.

The review rightly points out the obvious shortage of investigation in the cooling application area of the technology and suggests possible investigation area for improving its cooling applications.

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